ISBN 0-7743-9538-9

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A SYNOPTIC CLIMATOLOGY FOR OZONE IN SOUTHERN ONTARIO 1976-1981

June, 1984

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Ministry of the Environment

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ISBN 0-7743-9538-9

A Synoptic Climatology for Ozone in Southern Ontario - 1976 - 1981

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June, 1984

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Executive Summary

The synoptic climatology of ozone for Southern Ontario has shown that, over the 1976-1981 period, average summer ozone (0_3) concentrations follow a relationship similar to that reported for event analysis during periods of high 0_3 concentration. Highest average concentrations, 36 parts per billion (ppb), occur with "back of the high" situations while lowest average concentrations (20 ppb) occur with "front of the high" situations.

With similar weather events in the winter, the pattern is reversed with highest average 0_3 concentrations on the "front of the high" (19 ppb) and lowest average concentrations on the "back of the high" (13 ppb). Concentration of 0_3 in the "front of the high" sector is due in part, to the intrusion of 0_3 in the vicinity of storms from the stratosphere. The seasonal variation of average concentrations in these situations is low ranging from 14 to 26 ppb.

The very low average concentration during the winter and fall for the "back of the high" situation may be the result of scavenging by nitrogen oxides from the urban/industrial areas around the Great Lakes. During the spring and summer, solar energy and warm temperatures cause the photochemical production of 0_3 from nitrogen oxides and hydrocarbon precursors. In the fall and winter, photochemical production of ozone is either very low or absent, and the nitrogen oxides consume ozone rather than produce it. Thus, average 0_3 concentrations for winter "back of the high" situations are 1/3 of those in the summer months.

The synoptic climatology of events during the months from May to September with maximum ozone concentrations in excess of 80 ppb indicates that 78% of these events occur under synoptic weather classes generally indicative of back or centre of the high situations.

I. Introduction

The generation, build-up and dissipation of ozone concentrations in the atmosphere over Eastern North America have been studied by numerous researchers in recent years (e.g, Stasiuk et. al., 1975, Chung, 1977; Samson and Ragland, 1977; Vukovich et. al.; 1977, Wolff et. al. 1977; Wolff, et. al. 1982). Such studies suggest that the ozone concentration at any given location is the combined result of ozone originating from a number of different sources. These sources include (see Spicer et. al., 1979):

(i) natural or "background" tropospheric ozone.

(ii) ozone generated from local anthropogenic emissions.

(iii) ozone associated with long-range transport and accumulation in high - pressure weather systems.

(iv) ozone formed in the urban plume downwind of cities.

(v) ozone injected from the stratosphere into the troposphere and transported to the surface by convective mixing.

The above studies also indicate that the summer ozone life-cycle is strongly influenced by synoptic motion systems. Elevated ozone levels which tend to cover large regions of Eastern North America are found typically on the rear sides of anticyclones or in the warm sectors of cyclones. The associated transport mechanism has been identified with synoptic-scale motion systems which advect ozone and its precursors, nitrogen oxides and hydrocarbons, over distances of several hundred kilometers. On the resulting regional blanket of ozone, "hot spots" are formed by the ozone generated in urban plumes. It is thus apparent that synoptic scale meteorological

conditions related to long range transport need to be well understood in order to explain the occurrences of elevated ozone concentrations and to develop effective control strategies.

A. Ozone Episodes

Ozone episodes in Southern Ontario are typically associated with high pressure systems which form and move southward out of Central Canada into the Midwest of the United States or the Great Lakes area and then eastward to the Atlantic Coast (Wolff et. al., 1977, 1982). In general, the following observations of the relationship between ozone episodes and synoptic weather situations are noted (e.g., Yap and Chung, 1977) and schematically shown in Figure 1.

1. Ozone concentrations at the surface begin to increase when the ridge of an anticyclone passes over the region or with the passage of a warm front and the onset of regional southerly flow and warm temperatures. (The genesis ozone stage.)

2. Widespread elevated ozone concentrations (typically 80-150 ppb) are maintained during persistent south/southwest winds and warm temperatures, when the northwest sector of the anticyclone or the warm sector of a cyclone well ahead of the associated cold front covers the region, and the air has passed previously over areas of high precursor emission density. Ozone values in excess of 150 ppb may

occur on the back side of the high pressure system when the anticyclonic centre is well to the southeast of the lower Great Lakes region, often over or just off the Mid-Atlantic Coast and quasi-stationary (slow movement eastward). (The mature ozone stage.)

3. As the anticyclone drifts eastwards, and the region comes under the influence of an approaching cold front or the cyclonic center itself, ozone levels are variable. (The mixed and dissipation ozone stage.)

4. Low ozone values (typically $<$50 ppb) occur on the arrival of new anticyclones after cold frontal passages in the forward side of anticylonic systems with northerly flow, near neutral stability, and reduced temperatures (The "background" or natural ozone stage.)

Such elevated ozone episodes in the Midwest and Northeast United States and Southern Canada are generally confined to the late spring and summer months. Wolff et. al., (1977) indicate a typical time interval of 6-8 days from the high pressure system's entry into the upper Midwest until its departure into the Atlantic. It should be noted that climatological statistics show that this movement is along one of the principal tracks of anticyclones in the summer (Klein, 1957). The frequency of these ozone episodes, however, varies

considerably from year to year due to fluctuations in global weather patterns. For example, an analysis of "episode days" (days on which elevated ozone levels over 80 ppb occurred simultaneously over widespread areas at more than 8 monitoring sites) in Southern Ontario for the five year period 1976-1981 shows a maximum of 43 days of widespread elevated levels (maximum hourly concentration > 80 ppb) in 1978, and a minimum of 14 such events in 1979 and 1980.

This variability is also manifested in studies of warm, stagnating anticylones and associated ozone episodes in the United States (e.g, Korshover, 1975 and Altshuller, 1978). For Eastern North America, warm stagnating anticyclones occur predominantly between May and October (72% of the time) and impact the geographical area including the midwest, mid-Atlantic and southeast United States. The July 1974 ozone episode (described by DeMarrais, 1979 and Vukovich, 1979), for example, affected an area of about 1 million square kilometres of the eastern United States. The number of stagnations during the period May to October shows considerable variation from year to year (from as little as one stagnation of 5 days duration to as many as 10 stagnations covering a total of 57 days can occur in any one year (Altshuller, 1978)).

In addition to the typical ozone episodes described above with the air mass source region in Canada, other patterns have also been noted. Wolff and Lioy (1978) described one such episode (during the July 1977 heat wave) which was associated with a high pressure system that formed over the Southeast United States and remained

nearly stationary. High ozone was associated with the southwest flow of air around the high pressure system forming an "ozone river" from Texas to Southern New England. The geographical extent of this episode covered nearly two-thirds of the eastern quadrant of the U.S. (approximately 5 million square kilometres) and also southern Canada (Shenfeld et. al., 1978), with ozone concentrations greater than 100 ppb over most of the area from the Plains states eastward. In the Northeast, levels were above 200 ppb and on one occasion exceeded 300 ppb. It was also estimated (Wolff and Lioy, 1978) that air parcels with ozone concentrations of 90-130 ppb travelled about 2300 km in 48 hours.

B. Source Contribution to Ozone Burden

As indicated previously, ozone monitored at any location is the combined result of natural tropospheric background levels, stratospheric contributions, mesoscale and synoptic scale transport, and local atmospheric chemical reactions. The fraction caused by each source is generally difficult to ascertain (Lyons and Cole, 1976). An example of the approximate contributions of various sources to the total ozone burden has been provided by Spicer at. al., (1979) for the Northeast Oxidant Study based on Fluorocarbon-11 vs. O_3 extrapolations, air mass trajectory analysis, ozone distribution maps and vertical and horizontal cross-sectional O_3 distribution. In this study, maximum background O_3 (e.g. from natural emissions and stratospheric origin) and O_3 generated from rural emissions were estimated to contribute 20-45 ppb hourly average and 20 ppb daily average to the ozone burden while regional O_3 associated with the warm sector of high-pressure systems contributed 70-150

ppb to the hourly averages. The maximum hourly average 0_3 generated within urban plumes was estimated to be 150-250 ppb. These urban ozone plumes were typically distinguishable up to 100 km downwind. Over coastal waters, such plumes were observed to remain distinct for 240 km or more.

Recent studies of the relationship between 0_3 and Beryllium -7 in the Eastern United States during episodes of high 0_3 concentration (Wolff et. al., 1979, Wolff, et. al., 1982) conclude that the contribution of stratospheric ozone during these episodes appeared to be significant (30-50 ppb). Beryllium-7 is formed in the stratosphere by cosmic ray bombardment and therefore may be used as a tracer of stratospheric air in the troposphere. Stratospheric ozone enters the troposphere at a folding of the tropopause in the vicinity of an upper air trough. The amount of 0_3 brought downward is related to trough intensity as determined by the 500 millibar maximum wind speed. The stratospheric ozone, when brought to the surface through convective mixing, may then be advected to the back side of a high pressure system in the airflow around the anticyclone centre to combine with ozone from other sources.

C. The Ozone Problem in Ontario

In the late 1950's, tobacco growers in the area north of Lake Erie were losing millions of kilograms of tobacco to a disorder known as "weather fleck" (Mukammal, 1960). Weather fleck was found to occur most frequently on sunny days with high temperature and dew point and poor visiblity due to haze or smoke. These days were also characterized as having a southwesterly airflow and occurring after the passage of a maritime tropical or modified

maritime polar air mass. The cause of weather fleck was later found to be high concentrations of ozone (MacDowell, et. al., 1964).

The measurement of total oxidants began in the Ontario air quality monitoring network at selected sites in 1969. In 1973, a monitoring instrument using chemiluminescence techniques became available to measure ozone specifically and the oxidant monitors began to be replaced with the ozone monitor. By 1975 all Ontario sites were using the chemiluminescence instrument. The monitoring network has expanded in recent years from 16 sites in 1975 to 36 in 1981. The network has been expanded to include rural sites as a result of concerns for the long-range transport of ozone into Ontario and of the damage by ozone of crops such as white beans.

II. The Ontario Ozone Monitoring Network

A. Monitoring Method

The chemiluminescence method was the method used for the measurement of ozone in the ambient air in Ontario during the period of this study. In the chemiluminescence method, ambient air is drawn into a reaction chamber and then mixed with ethylene. Any ozone in the sample reacts instantaneously with the ethylene and in the process emits visible light with peak emission at 440 nanometers. The light intensity, which is directly proportional to the ozone concentration, is measured with a photomultiplier tube and the electronic output of the photomultiplier tube is fed to an output storage device (strip chart recorder or magnetic tape). The instrument is capable of monitoring ozone concentrations between 1 and 500 parts per billion by volume.

B. Station Locations

The 1981 network of 36 ozone monitoring sites included 32 sites in Southern Ontario (Figure 2), eight of which were located in Metropolitan Toronto. Fourteen of these sites, indicated by underline in Figure 2, have been chosen for climatological study in this report. These stations were chosen to give the best temporal and spatial resolution to the study. Station locations are given in Table 1 along with a designation as to whether the site is considered urban or rural. Note that stations in Sarnia, Toronto and Oakville were relocated during the 1976-1981 period used in this study. The distance of the move was considered inconsequential with regard to continuity of ozone data, however, and the data from the two stations have thus been combined into a single record for this study.

III. Synoptic Climatology of Ozone in Southern Ontario

Previous studies of high concentration ozone events in Southern Ontario (Yap and Chung, 1977, Shenfeld, et. al., 1978) have shown that high concentrations occurred when an anticyclone was located to the east and low concentrations when the anticyclone was located to the west of the Province.

In order to quantify the climatological concentrations of a pollutant associated with various synoptic weather patterns, eight classifications were defined to categorize them (Heidorn, 1978). For this ozone study, five of these categories were used. Two of the remaining three occurred too infrequently to be statistically

significant. The third classification was for those days with no definite synoptic pattern. The classifications used in this study were defined as:

Class 1: Post-cold front/pre-high pressure ridge: in this class, high pressure is to the west of the study area and the gradient flow generally has a northerly component. Cold frontal passage may have occurred on the previous day.

Class 2: High pressure ridge: the study region is within or near the center or ridge of a high pressure system (anticyclone). This class was further subdivided as to whether it moved over Southern Ontario from the north, south or west.

Class 3: Post ridge/pre-warm front: highest pressure is to the east; gradient winds generally have a southerly components. A warm front or cyclone may pass on the following day.

The above three classes are associated with the movement of a cell of high pressure. They occur the most frequently of all classes accounting in total for 55% of the synoptic conditions during the 1976-1981 period.

Class 5: Cyclonic: the study area contains a cell of low pressure often with associated fronts or is influenced by a major cyclonic storm system adjacent to the study area. This class occurred 20.6% of the time.

Class 6: Cold front: a cold front passes through the area and is associated with a low pressure system some distance from the study area.

Classes 5 and 6 along with Class 4 (warm front-defined similarly to Class 5: cold front) are associated with low pressure systems (cyclones) either weak or of storm intensity. These classes in total account for 32.9% of the synoptic patterns during the 1976-1981 period.

The synoptic weather pattern for each day in the 1976-1981 period was classified according to the above scheme subjectively by examination of the 0700 EST surface weather map for the day in question (Summaries of these distributions are given in Appendix A.) For each of the fourteen ozone monitoring sites, the 24-hour average ozone concentration was paired with the appropriate synoptic weather class. Since the magnitudes of ozone concentrations are strongly seasonal, the data were further partitioned by season. Seasons were defined as:

1. Winter: 23 December to 22 March,
2. Spring: 23 March to 22 June,
3. Summer: 22 June to 22 September,
4. Autumn: 23 September to 22 December.

IV. Seasonal Synoptic Ozone Climatology

Mean seasonal and annual ozone concentrations are given in Table 2-6 for each of the weather classes and for all sampling days. In general, highest ozone concentrations occur in the summer followed by

spring, winter and fall. Concentrations for weather class 3 were the highest in the summer and spring, and weather class 1 concentrations were generally highest in the fall and winter.

A. **Winter** (See Table 3)

During the winter, air temperature and solar radiation intensity are at their lowest levels, and therefore photochemical ozone formation in the lower atmosphere is at its minimum rate. The alternate source of ozone is the upper atmosphere. This ozone may be brought from the stratosphere to the troposphere in the vicinity of intense cold fronts, a common winter phenomenon. This ozone would enter the lower atmosphere in the post-cold front/pre-high pressure ridge (Class 1) situation.

Average winter ozone concentrations were generally found to be highest during Class 1 situations (11-28 ppb). The likely source of this ozone is the stratosphere with intrusion occurring in the vicinity of cold fronts.

Weather Class 3, the back of the high situation, which accounts for most of the ozone episodes during the warm months has the lowest ozone concentrations (7-21 ppb) for many of the stations in the winter. The dramatic change in the difference between Class 1 and Class 3 from the warm season relationship may be due to the long-range transport or the local emission of nitrogen oxides which, because of the unfavorable conditions for photochemical reactions in the cold season, act as a scavenger of ozone rather than a precursor to its formation.

A breakdown of Class 2, high pressure cell or ridge over the area, into its location previous to the day in question (north, south, or west) does not show any preferred location for either high or low average ozone concentrations. Class 2, in general, has average concentrations lower than Class 1 and higher than Class 3. Classes 5 and 6 are generally higher that Class 3. Since cold fronts are associated with both these classes, stratospheric intrusion of ozone may be the source.

B. **Spring** (See Table 4)

During the spring, air temperature begins to increase along with solar radiation intensity to provide for favorable photochemical conditions for the formation of ozone in the lower atmosphere. Spring, especially early spring, is also characterized by passage of intense storms over Southern Ontario which may bring stratospheric ozone to the lower atmosphere.

Highest average ozone concentrations generally occur with Class 3 situations with levels nearly three times the winter average for this class. Lowest average concentrations are found on Class 5 or Class 1 days.

The average concentration for all days is high in spring and does not differ significantly from summer average concentrations. Spring class 3 averages are slightly lower then the summer but class 1 averages are higher than in the summer. The higher Class 1 concentrations may be due to increased O_3 production in the stratosphere as solar radiation increases and intrusion takes place in the vicinity of spring storms.

C. **Summer** (See Table 5)

In the summer, highest average ozone concentrations occur under Class 3 situations and lowest under Class 1. Anticyclones moving from the south (Class 2S) have higher average concentrations than those from north or west. The average ozone pattern for summer closely follows the general scenario for high ozone periods discussed elsewhere in this report.

Summer cyclones (Class 5) are generally not intense enough to consider stratospheric intrusion as a major source of ozone. They often are not associated with extensive cloud cover as in other seasons, and, therefore, ozone concentrations may rise to exceed the 80 ppb criterion in the region of southerly flow between the associated warm and cold fronts.

D. **Fall** (See Table 6)

Declining air temperatures and waining solar radiation bring the average fall ozone concentrations to its lowest levels. Weather Class 1 has the highest fall average concentration. The remaining classes are quite close in average concentration, and no general pattern can be discerned.

E. **Discussion**

Seasonal average ozone concentrations for 14 sites in Southern Ontario show the highest values in spring and summer (27 ppb), lower values in winter (16 ppb) and the lowest values in the fall (12 ppb) when all days are taken into account (Table 7). When the data are partitioned according to prevailing synoptic weather class, two distinct patterns emerge.

In the cold seasons (fall and winter) ozone concentrations are highest under Class 1 synoptic conditions likely due to the introduction of stratospheric ozone into the lower atmosphere behind a cold front. In the winter, ozone under Class 3 conditions has the lowest concentration. A likely explanation for this minimum is the long-range transport of ozone-destroying nitrogen oxides. All other classes show similar concentrations.

In the warm season (spring and summer), ozone concentrations are high with Class 3 conditions and low in the spring with Class 5 and in the summer with Class 1. The Class 3 ozone is mainly due to photochemical formation of ozone and the transport of ozone or its precursors-often over long distances.

Average ozone concentrations are generally highest in the southwest portion of the study region and lowest in the east. Ozone concentrations in Metropolitan Toronto and other urban areas are depressed due to nitrogen oxide scavenging. These generalizations apply to all seasons and weather classes. While the magnitude of the concentrations differed significantly between monitoring locations, the relative differences between weather classes and seasons for these sites are similar with few exceptions.

V. Synoptic Climatology of Periods of Elevated Ozone

The synoptic climatology of ozone reported above gives an indication of average O_3 concentrations with various weather situations. Much of the attention, however, is generally focused on periods when O_3 concentrations exceed the Provincial criterion of 80 ppb. A synoptic climatology of periods during which maximum hourly concentrations exceeded 80 ppb, therefore, has been prepared.

Twelve of the fourteen monitoring stations used in the O_3 synoptic climatology have been examined for days on which the maximum hourly O_3 concentration exceeded 80 ppb. These stations are located in Windsor, Huron Park, Sarnia, London, Simcoe, Kitchener, Oakville, Etobicoke, Toronto, Scarborough, Ottawa and Cornwall. Since most of these events occurred during the warm season, data for the period May through September for the years 1976 - 1981 were used in this study.

Table 8 gives the percentage distribution of days when the maximum hourly O_3 concentration exceeded 80 ppb for each synoptic class when: 1) at least one of the twelve stations reported an event; 2) at least three stations reported an event; and 3) at least five stations reported an event on the same day. The majority ($\sim$60%) of these days occurred, as expected, with Class 3 (back of the high) and Class 2 (centre of the high) situations. Class 8 days (weak pressure gradient) accounted for about 10%. The least percentage of event days (1-3%) occured under Class 1 (front of the high) situations.

Two of the Class 1 days deserve special note as more than 5 stations reported ozone in excess of 80 ppb. The first, June 4, 1977, was distinguished by a high pressure centre over Ohio with a ridge extending into lower Michigan. This high was moving southeastward which brought most of southwestern Ontario into a westerly flow of air that had crossed northern Illinois, Indiana and lower Michigan by afternoon. This situation is similar to a back of the high situation although it is classified, according to the definition, as Class 1.

A high pressure cell centered over Lake Michigan characterized the synoptic situation on August 22, 1978, and Southern Ontario was in a Class 1, front of the high, situation. The history of this high, however, is of interest. On the previous day, the cell had been centered over lower Michigan with a ridge extending northeast to the Gulf of St. Lawrence. On the following day (August 23), a stationary front running along Lake Erie split the high into two cells with pressure maxima in West Virginia and just south of Hudson's Bay in Northern Ontario. The ridge was weakening and quasi-stationary. Winds in Ontario were generally light and variable. Near the lakeshores, winds typical of lake breeze regimes prevailed.

Seven stations exceeded the 80 ppb O_3 concentration with an eighth peaking at 79 ppb. Of the sites, three were in the Metropolitan Toronto and one each in Oakville, Sarnia, Windsor and Huron Park. The 79 ppb was measured at Simcoe. Only Huron Park is sufficiently removed from the lakeshore to not be certain to be under the influence of a lake breeze regime. It is therefore suggested that the cause of the high ozone concentrations was related to mesoscale formation and transport over the

Lakes with subsequent inland flow during lake breeze regime. This phenomenon has been reported in some detail by Mukammal (1965), Lyons and Cole (1976), Anlauf, et. al. (1976), Westberg, et. al. (1981) and Mukammal et. al. (1982).

The average maximum O_3 concentration and the average number of hours reporting O_3 concentrations above 80 ppb on an event day were determined for each station for each weather class. No patterns emerge as to variations between weather classes for the number of hours above 80 ppb. All weather classes generally reported an average of between 4 and 6 hours above 80 ppb per day on event days. Average maximum ozone readings generally were within 90-100 ppb. The Class 7, stationary front, situation was the only class to deviate markedly from this pattern showing a range of 98-110 ppb. Since stationary fronts are characterized by very restricted vertical and horizontal mixing of the air mass, it is not surprising that maximum O_3 concentrations are higher than for other weather situations.

The final question to be asked is "Was there a relationship between the number of days with synoptic conditions conducive to high O_3 concentrations and the number of hours greater than 80 ppb during the months of May through September?

In order to answer this question, the total number of hours of ozone above 80 ppb for the monitoring network (approximately 30 stations) was summed and the average number of hours per station determined. This number was linearly correlated for each year 1976 to 1982 with the number of days on which certain weather situations

occurred during the May-September period. Classes 2,3 and 8 accounted for 65% of the weather situations on days with the O_3 concentrations over 80 ppb. The correlation for the total number of days with Class 2,3 or 8 and the average number of hours above 80 ppb was poor ($r^2 = 0.17$, $r = 0.41$) as was the correlation with the total number of days with Class 3 situations ($r^2 = 0.008$, $r = 0.28$). Next the annual number of period with consecutive days of Class 2,3,4 or 8 were correlated with exceedences. The resulting correlations were again low: $r^2 = 0.11$, ($r = 0.33$) when the period consisted of at least a 3-day string of days and $r^2 = 0.22$ ($r = 0.47$) when the string was at least 5 days in length. The best correlations occurred when a string of at least two consecutive days were under Class 3 conditions ($r^2 = 0.68$, $r = 0.82$) or at least two consecutive days were under Class 3 or Class 8 conditions ($r^2 = 0.67$, $r = 0.82$).

It is realized that averaging the number of exceedences of 80 ppb for the network may be uneven due to their distribution across the network and between urban and rural sites. Therefore, similar correlations have been calculated with the total number of hours above 80 ppb concentration for Simcoe (a rural site) and London (an urban site) versus weather situations.

Correlations coefficients for Simcoe were $r^2 = 0.42$ ($r = 0.65$) of total number of days with Class 2,3 or 8; $r^2 = 0.39$ ($r = 0.62$) for the total number of Class 3 days; $r^2 = 0.06$ ($r = 0.24$) and $r^2 = 0.23$ ($r = 0.48$) when a period consisted of a string of 3 or 5 days respectively of Class 2,3,4 or 8 situations respectively; $r^2 = 0.51$ ($r = 0.71$) and $r^2 = 0.60$ ($r = 0.77$) when 2 or more consecutive days were Class 3 or 8 situations or Class 3 only situations respectively.

Correlation coefficents for London were $r^2 = 0.12$ ($r = 0.35$) and $r^2 = 0.26$ ($r = 0.51$) for the total number of hours above 80 ppb and the number of days with Class 2,3, or 8 situations or Class 3 situations respectively; $r^2 = 0.39$ ($r = 0.62$) for the number of periods with at least 3 consecutive days of Class 2,3,4 or 8 and $r^2 = 0.32$ ($r = 0.57$) when periods consisted of 5 or more consecutive days of Class 2,3,4 or 8; $r^2 = 0.57$ ($r = 0.75$) for periods with at least 2 consecutive days of Class 3 or 8 and $r^2 = 0.55$ ($r = 0.74$) for periods of at least 2 consecutive days of Class 3.

The above analyses show that there is a tendency for more hours of O_3 concentrations in excess of 80 ppb when there are two or more consecutive days under Class 3 or 8 conditions. The correlation with the total number Class 3 days alone was generally poor, due in part to the rather consistent number of Class 3 days per year. A similar poor correlation for Class 2,3 and 8 days was found. The small year-to-year variation in the number of these days is again the likely cause of the low r^2.

Although days with weather patterns conducive to high O_3 concentrations occur with approximately the same frequency each year, there is a wide range in the number of hours exceeding 80 ppb concentration. It may be concluded that years in which conducive weather patterns frequently remain over Southern Ontario for several days are more likely to have a higher total number of hours in excess of 80 ppb. This may be linked to a regular flow of ozone and its precursors from the area south of the Great Lakes. This may be especially true for the concept of an "ozone river" proposed by Wolff and Lioy (1978) where ozone flowing above the surface layer is able to traverse great distances in substantial concentrations without extensive nocturnal consumption by nitrogen oxides.

VI. Conclusions

The synoptic climatology of ozone for Southern Ontario has shown that, over the 1976-1981 period, average ozone (0_3) concentrations follow a similar relationship to that reported for event analysis during periods of high 0_3 concentration in the high-sun seasons (spring and summer). Highest average concentrations (36 ppb) occur with "back of the high" (Class 3) situations while lowest (20 ppb) average concentrations occur with "front of the high" (Class 1) situations.

With similar weather events in the low-sun seasons (fall and winter), however, the pattern is reversed with highest average 0_3 concentrations on the "front of the high" (19 ppb) and lowest average concentrations on the "back of the high" (13 ppb).

While the scope of this study cannot definitely prove the reason for this reversal, some hypothesis may be put forth. It is suggested that the concentration of O_3 in the "front of the high" sector (Class 1) during the low-sun seasons is due to the stratospheric intrustion of O_3 in the vicinity of storms. The seasonal variation of average concentrations in this class is the lowest of the five classes ranging from 14 to 26 ppb. This range is close to the reported mean annual ozone burden from the stratosphere in the northern United States of 30 ppb (Kelly, et. al. 1982). Kelly et. al. (1982) also reported that stratospheric ozone concentrations are lower in the summer than the winter.

The very low average concentration during the low-sun seasons for the "back of the high" situation may be the result of scavenging by nitrogen oxides emitted into the atmosphere from the

urban/industrial areas south of or around the Great Lakes. During the high-sun seasons, solar energy and warm temperatures cause the photochemical production of O_3 from nitrogen oxides and hdyrocarbon precursors. In the low-sun seasons, photochemical production is either vary low or absent, and the nitogren oxides consume ozone rather that produce it. Thus, average O_3 concentrations for winter Class 3 are 1/3 of those in the summer months.

Thus, while the Class 1 average concentrations are of the same magnitude for all seasons ($\sim$20 ppb) it is suggested that the Class 3 averages are depressed in the low-sun seasons and enhanced in the high-sun seasons due to the presence of nitrogen oxides emitted from sources in and south of the Great Lakes airshed. Whether the nitrogen oxides are net producers or scavengers depends upon the amount of available solar radiation and the appropriate ozone precursor compounds such as the reactive hydrocarbons.

The synoptic climatology of events with maximum ozone concentrations in excess of 80 ppb indicates that 78% of these events occur under synoptic classes 2,3,6 and 8 during the months from May to September. These four classes are generally indicative of back or centre of the high situations.

A tendency toward more frequent exceedances of 80 ppb is seen in years when, during the months from May to September, there are more frequent periods when two or more consecutive days are either Class 3 or 8.

A number of questions raised, but beyond the scope of this study, are included here as direction for future research.

1) A detailed study of one or two events lasting over several days should be undertaken. While some preliminary work on event analysis may be done with presently available data, the question of long-range transport of anthropogenic ozone above the surface layer (i.e. the "ozone river") may require additional monitoring (such as vertical profiles).

2) The question of the stratospheric input of ozone to the surface layer should be studied further. The synoptic climatology estimates about 20 ppb of ozone arriving in flows from the north, a value nearly independent of the season. How much of this is stratospheric and how much is natural tropospheric background must still be determined.

3) The possible application of the statistical forecasting of ozone events from forecast weather parameters should also be persued. Some success has been achieved using Model Output Statistics (MOS) by Karl (1979) in predicting the probability of high ozone concentrations.

4) The relationship between nitrogen oxides and weather class should be developed in order to determine whether the depressed Class 3 winter O_3 concentrations are due to scavenging by NO_x compounds transported from distant sources or local sources.

5) The relationship between sulphate and nitrate particulates and ozone should be explored.

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Table 1

Ozone Monitoring Stations Used in Climatological Study

Station Number	Address and Location	UTM Grid Coordinates East	North	Site Designation	Dates Operating
10001	College of Agricultural Technology, Huron Park	04600	47931	rural	4/77-12/81
12008	467 University Ave. W, Windsor	03316	46867	urban	1/76-12/81
13021	MOE Pump Station, Merlin	03991	46776	rural	8/77-12/81
14049*	156 Victoria St., Sarnia	03854	47584	urban	1/76-7/78
14064*	Centennial Park, Sarnia	03878	47578	urban	7/78-12/81
15001	King-Rectory, London	04818	47595	urban	1/76-12/81
22071	Experimental Farm, Simcoe	05597	47449	rural	1/76-12/81
26029	Edna/Frederick Sts., Kitchener	05427	48116	urban	1/76-12/81
31001*	67 College St, Toronto	06300	48352	urban	1/76-6/81
31104*	26 Breadalbane, Toronto	06302	48356	urban	6/81-12/81
33003	Lawrence-Kennedy, Scarborough	06389	48452	urban	1/76-12/81
35003	Elmcreast Rd., Etobicoke	06142	48338	urban	1/76-12/81
44010*	1298 Rebecca St., Oakville	06053	48078	urban	1/76-3/80
44015*	Bronte Rd/Woburn Cres., Oakville	06031	48059	urban	3/80-12/81
48002	MTC Yard Hwy 47, Stouffville	06391	48694	rural	1/76-12/81
51001	McDonald Gardens, Ottawa	04471	50312	urban	1/76-12/81
56051	Memoral Park, Cornwall	05208	49846	urban	1/76-12/81

*Sites in Sarnia, Toronto and Oakville moved during period.

Table 2

Average Annual Ozone Concentration Versus Prevailing Weather Type (1976-1981)

	Average Ozone Concentration (ppb)								
	Weather Class								
Station	1	2T	2S	2N	2W	3	5	6	All Types
Huron Park	24.2	26.5	24.7	24.1	28.9	30.0	23.6	26.1	26.4
Windsor	15.9	21.6	13.9	21.1	23.5	21.2	14.8	19.9	18.9
Merlin	22.9	26.7	24.2	24.4	29.2	27.2	22.4	28.4	25.5
Sarnia	20.0	21.5	15.2	21.2	25.0	19.5	19.8	22.2	20.9
Simcoe	27.8	30.0	26.6	27.0	29.3	33.3	26.3	33.8	30.5
London	17.2	18.9	14.6	18.0	20.4	21.2	16.8	21.6	19.2
Kitchener	21.3	17.7	18.9	19.4	23.5	25.6	21.0	22.5	22.3
Toronto	15.4	15.8	11.1	14.4	18.4	17.8	13.9	18.3	16.1
Scarborough	12.6	15.2	10.1	14.6	16.7	17.6	12.7	14.7	14.8
Etobicoke	14.8	14.5	12.7	12.6	15.9	17.7	14.5	17.1	13.9
Oakville	19.1	21.1	16.4	20.3	21.1	22.6	17.4	21.0	20.4
Stouffville	25.7	27.9	22.6	26.7	28.3	27.1	23.0	25.3	25.4
Ottawa	18.1	16.9	13.7	16.7	17.3	18.8	15.1	18.1	17.2
Cornwall	19.7	21.6	17.6	20.1	24.8	25.4	19.6	24.4	21.8

Note: 2T refers to all Class 2 days
2S refers to anticyclone entering from the south
2N refers to anticyclone entering from the north
2W refers to anticyclone entering from the west

Table 3
Average Winter Ozone Concentration Versus
Prevailing Weather Type
(1976-1981)

Average Ozone Concentration (ppb)

Station	Weather Class 1	2T	2S	2N	2W	3	5	6	All Types
Huron Park	27.7	24.2	27.7	22.0	23.2	17.3	21.3	23.6	23.3
Windsor	11.7	10.4	9.6	10.4	10.5	8.9	9.8	9.2	10.5
Merlin	24.0	24.9	26.7	24.0	19.9	17.0	20.8	21.1	22.0
Sarnia	19.4	14.0	10.8	16.7	15.1	9.2	17.2	15.7	16.0
London	15.8	11.8	11.0	12.6	11.1	9.8	13.5	14.0	13.3
Simcoe	27.1	24.5	23.5	23.2	20.9	21.1	22.6	23.7	24.4
Kitchener	22.8	8.6	18.9	16.1	14.9	14.0	18.1	14.4	18.4
Toronto	13.2	8.9	8.7	8.3	13.8	8.3	10.2	11.8	10.5
Scarborough	11.5	8.8	7.9	9.6	8.7	7.9	9.7	7.9	8.6
Etobicoke	15.9	11.1	11.9	8.8	11.9	9.2	14.8	11.4	10.9
Oakville	17.7	13.7	13.3	13.9	7.2	12.0	14.1	12.6	14.5
Stouffville	24.8	22.1	19.8	20.9	23.2	15.6	20.0	15.7	20.8
Ottawa	17.2	13.0	12.9	13.0	13.9	10.4	13.3	11.5	13.6
Cornwall	20.8	19.1	18.0	17.0	22.7	17.0	17.0	18.9	18.5

Table 4

Average Spring Ozone Concentration Versus Prevailing Weather Type (1976-1981)

Average Ozone Concentration (ppb)

	Weather Class								
Station	1	2T	2S	2N	2W	3	5	6	All Types
Huron Park	27.6	31.8	29.1	30.0	35.3	38.4	27.2	29.6	30.4
Windsor	23.9	29.7	27.3	25.7	30.0	31.9	21.4	25.3	26.5
Merlin	30.0	36.6	34.0	30.7	40.7	39.6	29.7	33.3	33.6
Sarnia	25.6	27.2	22.6	24.7	31.1	29.1	25.2	25.9	26.7
London	23.4	25.1	18.4	22.6	27.4	30.5	22.4	26.5	25.1
Simcoe	36.2	38.8	33.6	34.2	43.5	44.0	35.1	40.9	39.4
Kitchener	28.4	26.0	24.8	25.9	29.5	36.6	28.5	29.9	28.9
Toronto	23.0	22.0	16.9	19.7	23.9	27.4	20.8	23.6	22.6
Scarborough	17.8	21.1	15.7	19.8	22.4	27.4	18.2	19.6	20.7
Etobicoke	19.7	18.0	15.8	16.7	18.5	25.4	16.3	20.8	18.9
Oakville	25.1	26.0	22.4	23.8	26.7	33.6	23.9	25.7	26.7
Stouffville	31.4	35.7	28.0	31.5	36.5	39.6	29.1	32.0	33.7
Ottawa	25.5	24.2	19.6	23.7	24.4	33.0	22.7	26.8	25.7
Cornwall	25.3	28.5	23.6	27.6	32.6	39.7	28.0	32.1	30.0

Table 5

Average Summer Ozone Concentration Versus Prevailing Weather Type

(1976-1981)

Average Ozone Concentration (ppb)

	Weather Class								
Station	1	2T	2S	2N	2W	3	5	6	All Types
Huron Park	22.0	32.4	43.3	25.7	34.2	44.9	30.0	30.1	33.3
Windsor	21.4	33.6	32.5	30.3	32.5	36.4	23.6	28.3	29.8
Merlin	24.9	31.7	35.2	28.2	33.5	42.1	30.6	34.1	34.1
Sarnia	20.0	30.9	35.8	26.7	31.9	32.9	27.4	28.0	28.7
London	18.6	26.0	34.8	21.8	25.2	36.0	25.0	28.3	27.7
Simcoe	28.6	36.2	47.5	28.6	35.9	43.7	35.1	42.3	39.3
Kitchener	20.1	28.8	37.5	20.2	30.4	43.2	28.5	27.9	30.0
Toronto	17.0	22.9	25.5	17.6	22.5	30.6	21.8	24.9	23.9
Scarborough	13.9	20.5	21.8	16.0	20.6	29.6	19.8	19.9	21.6
Etobicoke	15.2	20.4	22.8	15.4	21.3	31.7	22.9	22.7	22.3
Oakville	20.4	27.9	31.3	25.0	27.6	34.4	24.1	27.4	27.8
Stouffville	22.3	31.5	35.3	27.4	30.6	38.5	28.5	29.3	29.9
Ottawa	15.7	17.6	18.2	13.8	18.0	27.0	17.2	20.2	19.4
Cornwall	17.4	22.9	23.7	15.8	26.6	32.7	22.1	26.8	17.7

Table 6
Average Fall Ozone Concentration Versus Prevailing Weather Type
(1976-1981)

Average Ozone Concentration (ppb)

	Weather Class								
Station	1	2T	2S	2N	2W	3	5	6	All Types
Huron Park	20.5	15.1	15.1	14.3	14.2	16.6	18.0	16.5	17.2
Windsor	9.4	9.0	7.1	10.9	7.4	9.4	8.3	8.2	8.7
Merlin	16.1	14.2	15.0	14.9	13.3	14.2	14.0	13.4	14.2
Sarnia	16.0	11.8	9.8	12.9	11.9	9.7	13.2	13.4	13.2
London	12.0	9.2	8.0	9.5	8.9	9.2	9.6	10.2	9.8
Simcoe	20.6	17.7	17.7	17.5	16.7	19.6	17.5	19.9	18.7
Kitchener	16.6	10.0	11.5	10.8	9.7	12.0	12.8	12.4	12.7
Toronto	9.9	7.1	6.6	6.6	7.6	7.1	6.7	7.1	7.3
Scarborough	8.1	7.5	6.5	8.1	7.3	7.7	5.8	5.9	6.9
Etobicoke	9.0	6.1	7.5	4.8	5.8	7.3	8.1	8.2	7.8
Oakville	13.9	12.4	11.0	12.7	13.1	11.2	10.5	10.5	11.5
Stouffville	23.9	17.3	17.3	19.5	14.6	14.8	15.7	15.1	14.0
Ottawa	14.4	11.0	10.7	12.3	10.3	9.1	8.8	9.9	10.5
Cornwall	15.5	14.1	12.8	15.7	13.7	15.0	13.1	15.9	14.3

Table 7

Average Seasonal Ozone Concentration for 14 Stations in Southern Ontario by Synoptic Weather Classification (1976-1981)

	Average O_3 Concentration (ppb)					
	Weather Class					
Season	1	2	3	5	6	All Types
Winter	19.3	15.4	12.7	15.9	15.1	16.1
Spring	25.9	27.9	34.0	24.9	28.0	27.8
Summer	19.8	27.4	36.0	25.5	27.9	27.5
Fall	14.7	11.6	11.6	11.6	11.9	11.9

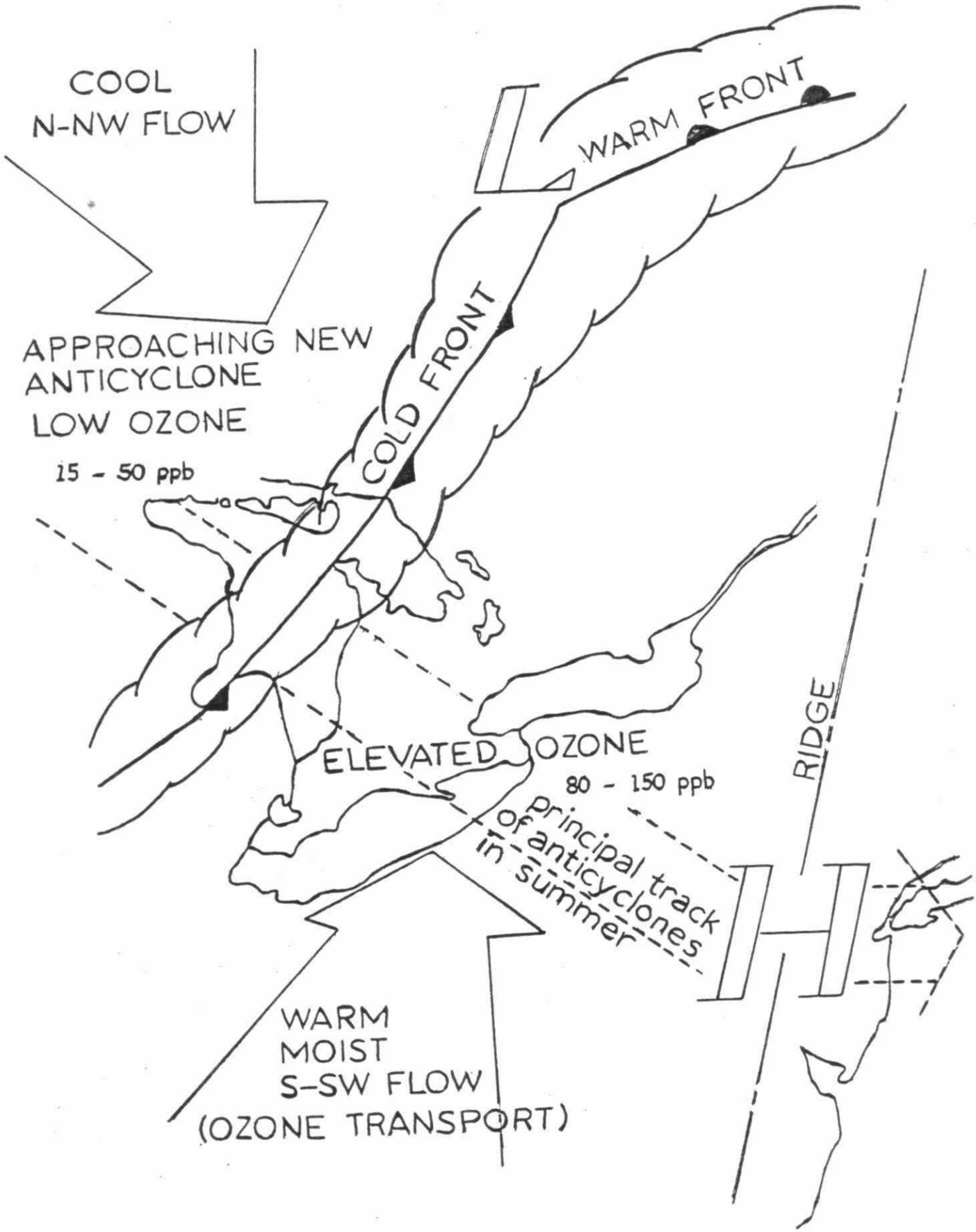
Table 8

Percentage Distribution by Weather Class of Days with Hourly Maximum Ozone Greater than 80 ppb for the the Months May- September, 1976-1981

	Percentage of Days with O_3 > 80 ppb		
Weather Class	1 or More Stations	3 or More Stations	5 or More Stations
1	3.4	1.1	1.8
2	26.8	30.0	26.6
3	27.3	30.5	32.7
4	2.8	3.2	2.6
5	7.5	4.7	5.3
6	12.6	7.4	5.3
7	8.0	10.0	13.3
8	11.6	13.2	12.4
Total Number of Events	388	190	113

Figure 1

Generalized Synoptic Weather Pattern Over
Southern Ontario With Associated Typical Ozone Concentrations



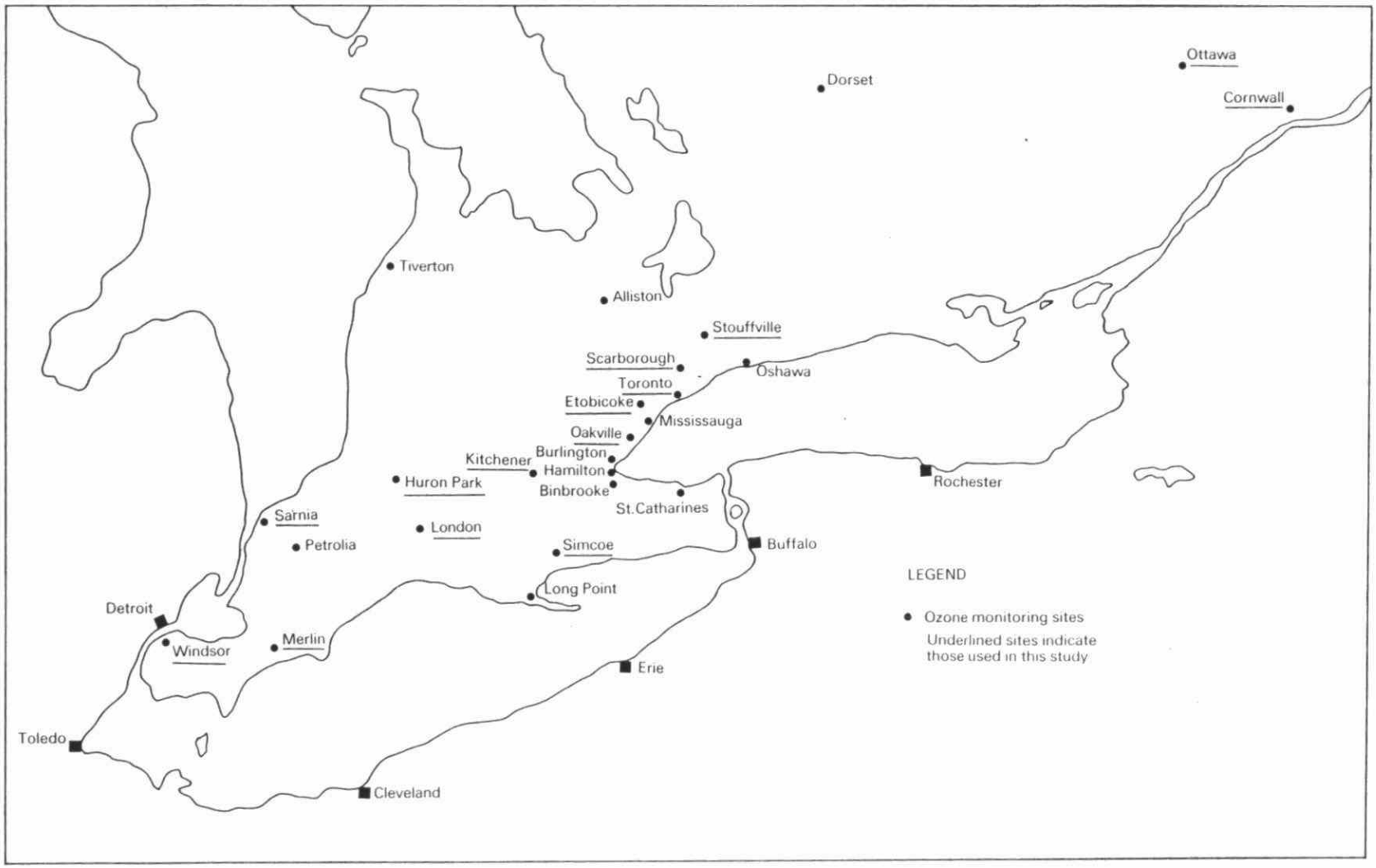


Figure 2: Location of Ozone Monitoring Sites in Southern Ontario

Appendix

Synoptic Weather Class Distribution 1976-1981

Daily weather maps for 0700 EST were examined to determined the predominant synoptic weather pattern influencing the Southern Ontario area (along a line from Windsor to Ottawa) for each day during the period 1 January 1976 to 31 December 1981. Eight weather classes were defined. They are:

Class 1: Post-cold front/pre-high pressure ridge: this class has highest pressure to the west and the gradient flow generally has a northerly component. Cold frontal passage may have occurred on previous day. (Figure A1).

Class 2: High pressure ridge: the area is within the centre or ridge of a high pressure system. (Figure A2).

Class 3: Post-ridge/pre-warm front: highest pressure is to the east; gradient winds generally have a southerly component. Warm frontal passage may occur on the following day. (Figure A3).

The above three classes are associated with the movement of a cell of high pressure.

Class 4: Warm front: a warm front passing through the area associated with a low pressure system not within the area. (Figure A4).

Class 5: Cyclonic: the area contains a cell of low pressure often with associated frontal passages or is influenced by major cyclonic storm system adjacent to the area (Figure A5).

Class 6: Cold front: a cold front passing through the area associated with a low pressure system not within the area. (Figure A6).

Classes 4 through 6 are associated with low pressure systems, either weak or of storm intensity. Classes 4 and 6 are to be used only when passage of the front is not associated with nearby cyclonic systems. An example of class 4 is a warm front sweeping the area from the southwest extending to a low moving northwestward across Lake Michigan. An example of Class 6 occurs when a storm system located in the vicinity of James Bay-Hudson Bay has an associated cold front extending across the Great Lakes.

Class 7: Stationary front: a stationary front lies through the area. (Figure A7).

Class 8: Weak pressure gradient: pressure gradient through the region is very weak; direction of flow is due to local influence rather than gradient wind, no clear influence of fronts or pressure system (Figure A8).

Classes 7 and 8 are weather conditions not tied to a specific wind flow pattern. In Class 7, the study area may be either to the north or south of the front.

Weather Class A2 was further partitioned to give the direction from which the anticyclone had come previous to the day on which it was over Southern Ontario. This was done because it was felt that the pollution burden may be different for anticyclones moving from the north, south, or west. The categories 2N, 2S, or 2W were only used on the first day of arrival of the anticyclone. When an anticyclone remained for more than one day, subsequent days were categorized as Class 2. Values for Class 2 in the tables are the sum of all days with anticyclone over the area (Class 2N + 2S + 2W + other Class 2 days).

Table A1 gives the annual distribution of the 8 weather classes for the period 1976-1981. Classes 5,1 and 2 occur most frequently: 20.6%, 19.6% and 19.4% respectively.

Class 3 occurs 16.0% of the time and the remaining classes less than 10%.

During the 1976-1978 period, Class 1 occurred more frequently than during the 1979-1981 period while Class 5 increased during 1979-1981 over 1976-1978.

Seasonal distributions of weather classes are given in Tables A2 to A5.

Winter (Table A2): Storm systems (Class 5) are the most frequent winter weather class - 28.8%. Class 5 and Class 1 account for over 50% of the observed classes.

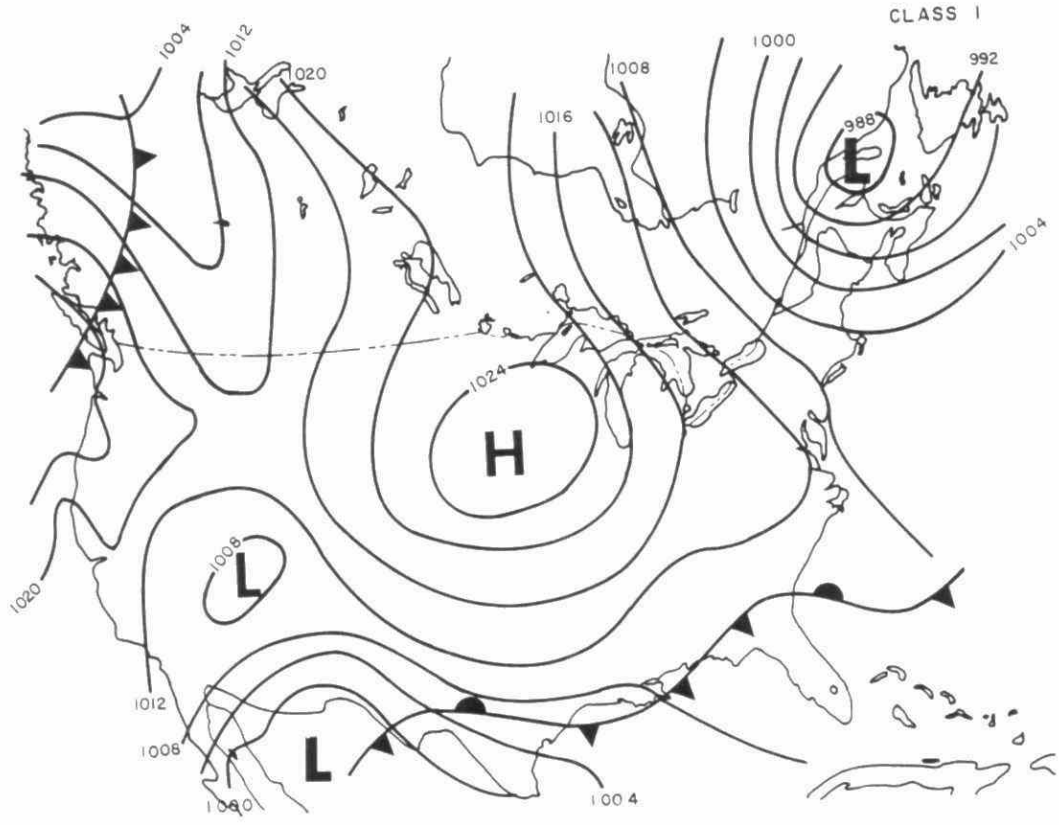
Spring (Table A3): Classes 2 (21.5%) and 5 (20.6%) are the most frequent classes with Class 1 at 18.0%. These three classes account for 60.1% of the days. The period 1978-1980 averaged 10 more Class 5 days than the other three years in the study. In 1980, Class 3 was about 10 days less frequent than in the other five years in this study.

Summer (Table A4): Class 2 is the most frequent summer weather type (21.2%) with Class 1 (16.3%) and 3 (16.1%) the next most frequent. These three classes account for 53.6% of the days.

1976, 1979 and 1981 were the stormiest years; Class 5 occurrences were about 10 days more frequent than in the other three years of the sample. Class 3 occurred significantly more often in 1977, 1978 and 1981.

Fall (Table A5): The most frequent weather classes in fall are Class 1 (22.2%), Class 5 (20.6%) and Class 3 (19.3%). There is a wide variation in the number of days for Class 1: 9 days in 1979 to 31 days in 1976.

Figure A1; Synoptic Class 1



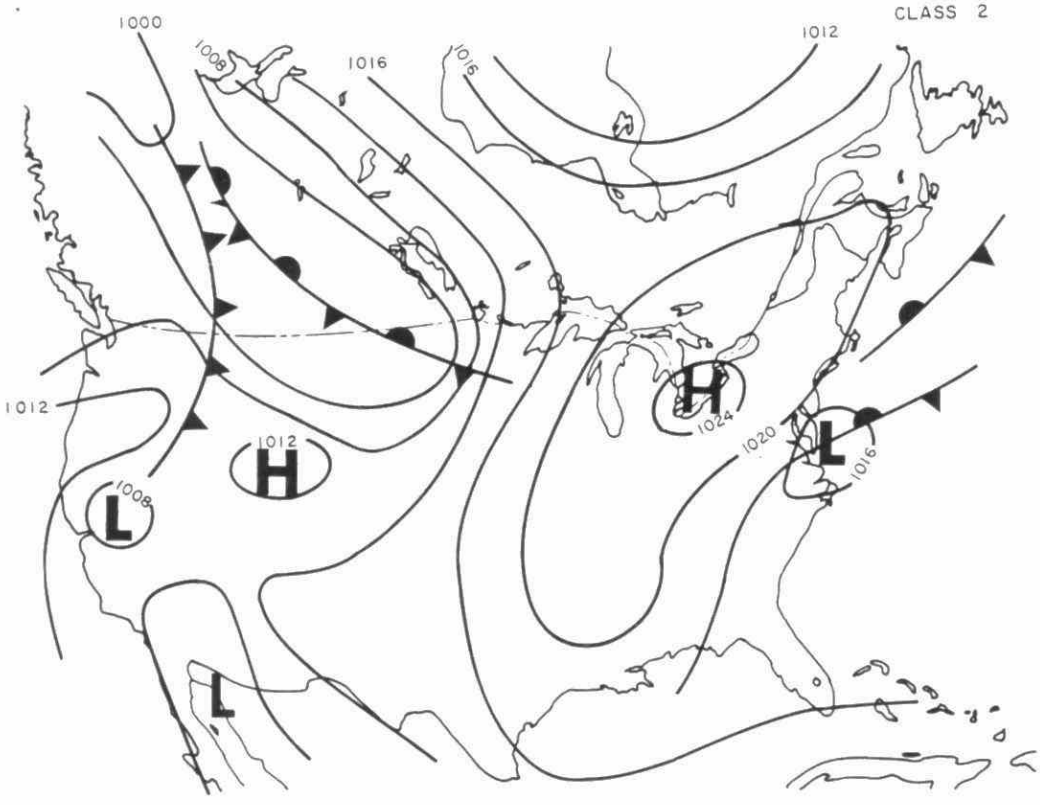
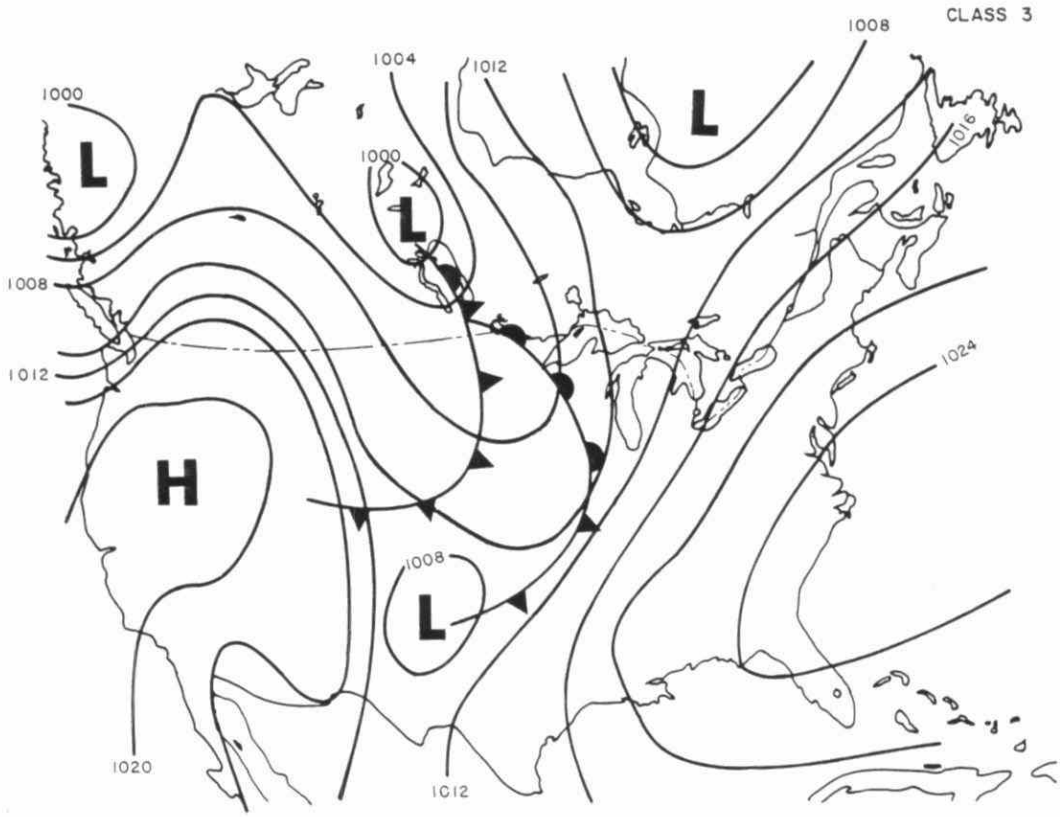


Figure A2: Synoptic Class 2

Figure A3: Synoptic Class 3



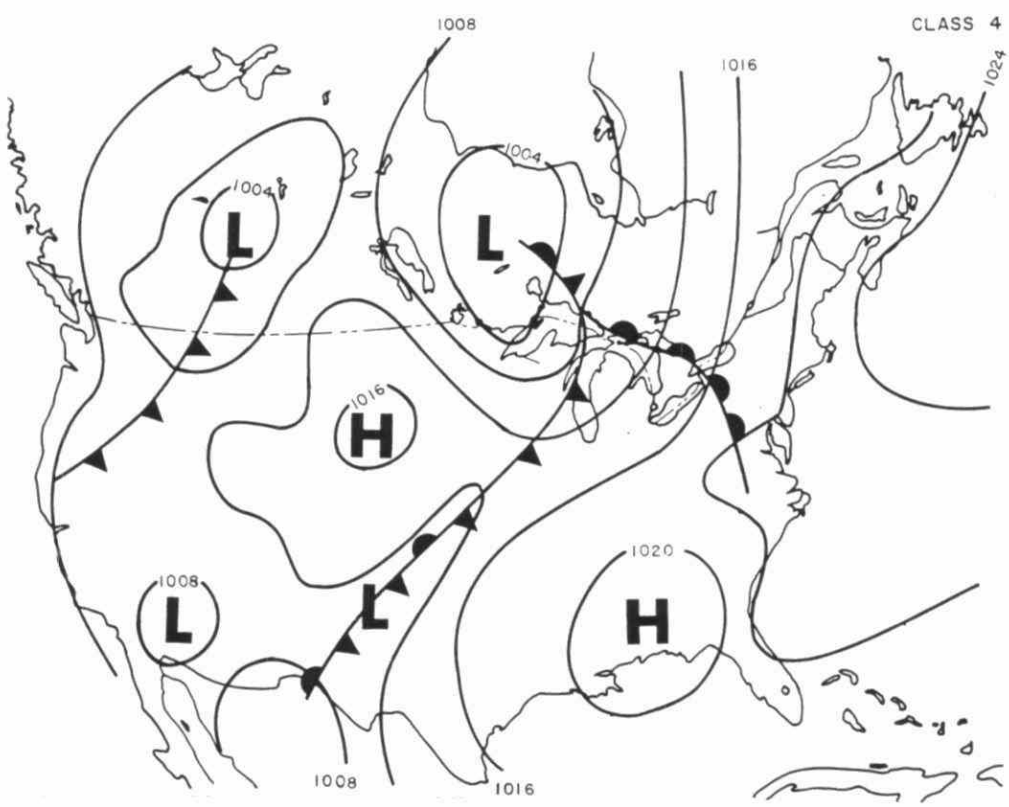
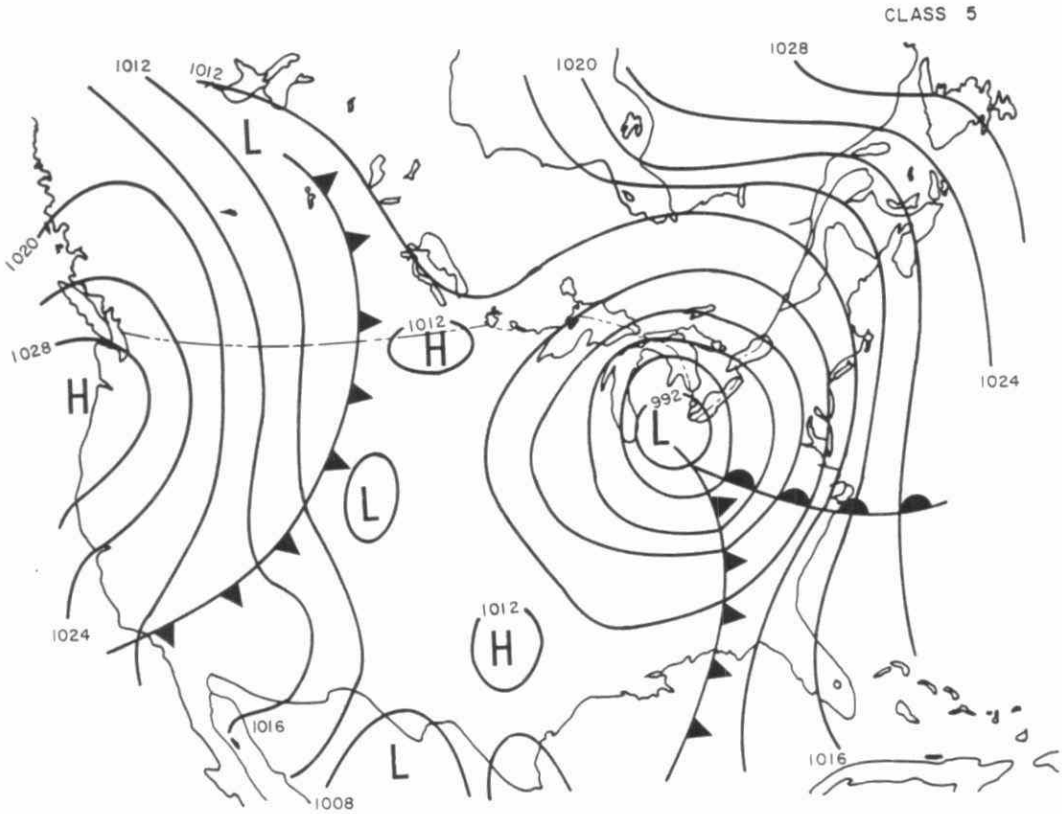


Figure A4: Synoptic Class 4

Figure A5: Synpotic Class 5



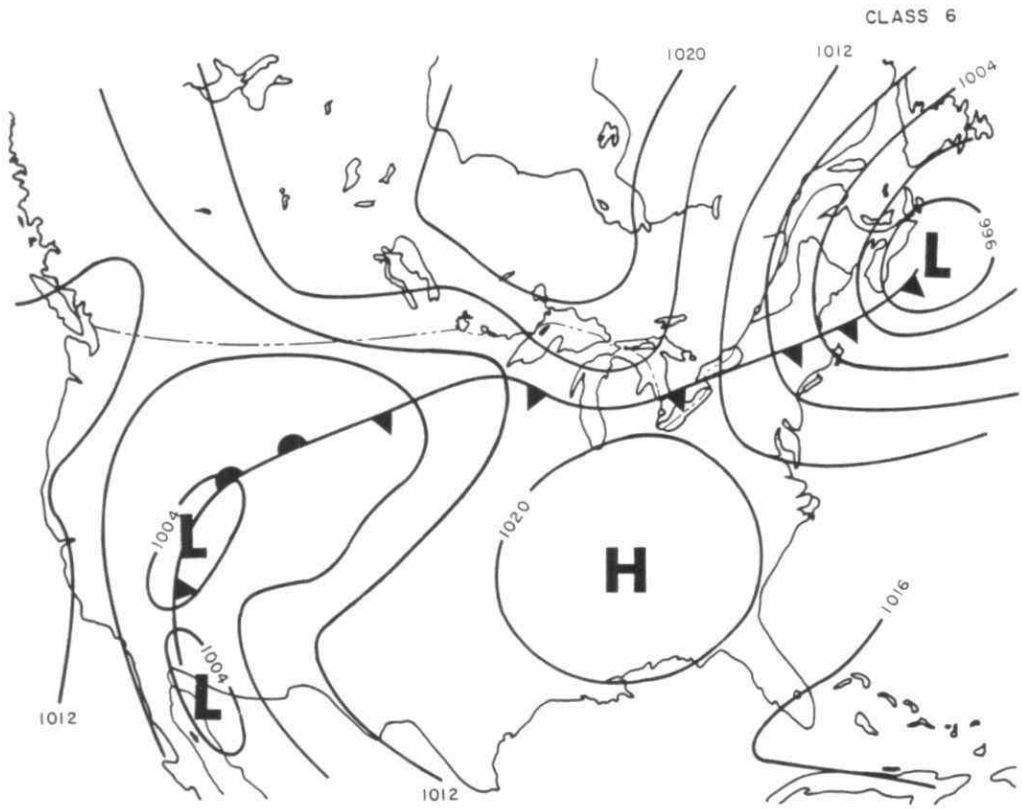
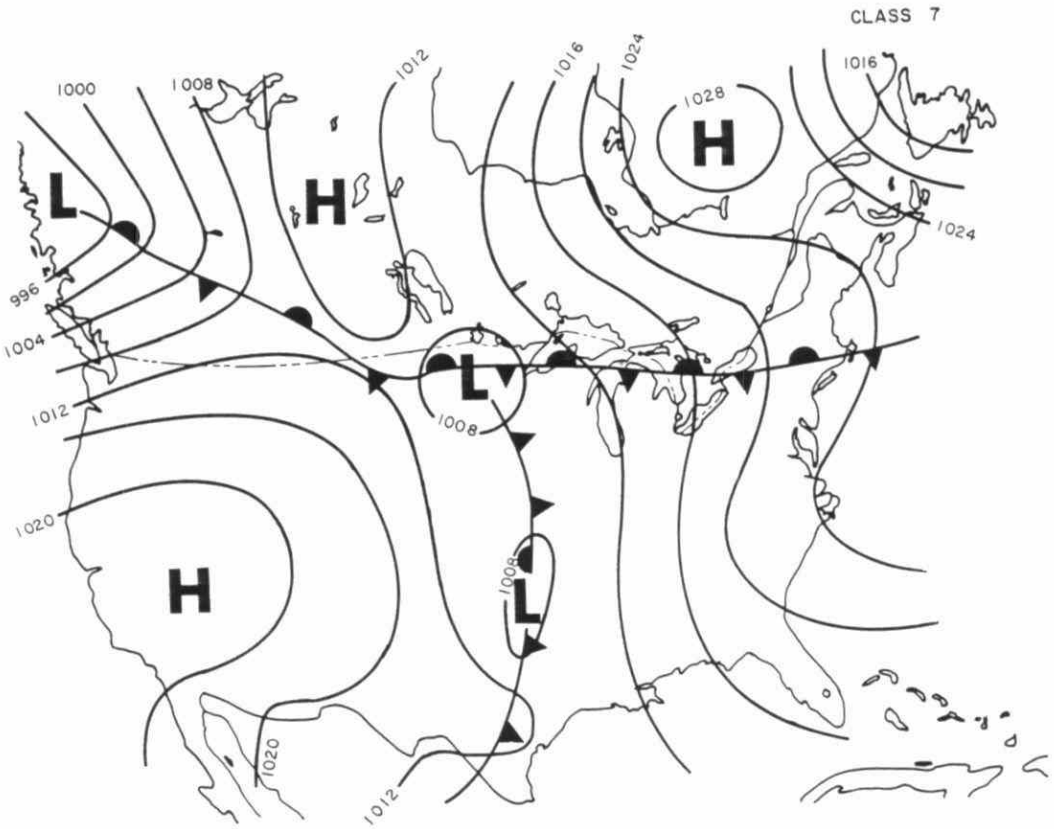


Figure A6: Synoptic Class 6

Figure A7: Synoptic Class 7



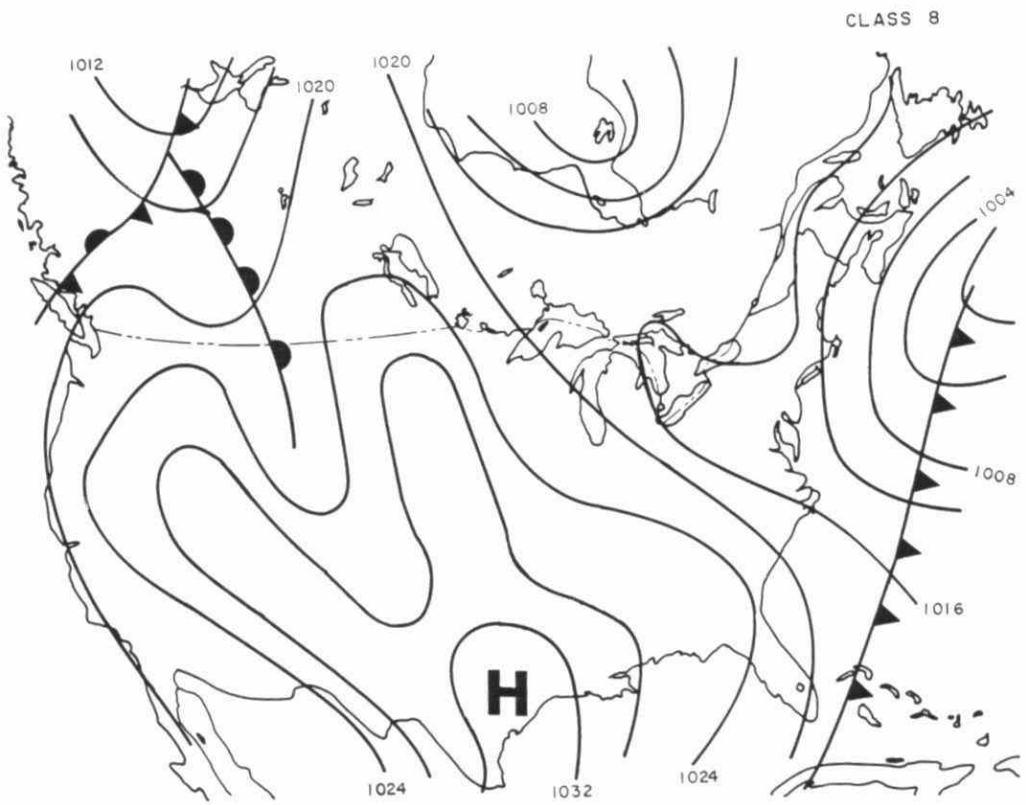


Figure A8: Synoptic Class 8

Table A1

Annual Distribution of Synoptic Weather Classes Influencing Southern Ontario - 1976 to 1981

	Weather Class										
Year	1	2	2N	2S	2W	3	4	5	6	7	8
1976	95	82	23	23	11	58	3	66	34	12	16
1977	89	58	22	20	6	72	6	54	26	16	44
1978	71	77	25	15	23	61	7	73	38	12	26
1979	51	68	21	9	19	55	16	96	28	8	43
1980	63	73	24	13	20	43	12	70	45	11	40
1981	59	64	27	8	19	59	10	90	42	4	33
1976-81 % Distribution	19.6	19.4	-	-	-	16.0	2.5	20.6	9.8	2.9	9.3
Annual Ave. Number of Occurrences	71	70	15	16	16	58	9	75	36	10	34
Standard Deviation	17	9	6	6	6	9	5	16	8	4	11
Std. Dev./Ave.	.24	.13	.40	.38	.38	.16	.56	.21	.22	.40	.32

Table A2

Winter Distribution of Synoptic Weather Classes Influencing Southern Ontario 1976-1981

	Weather Class										
Year	1	2	2N	2S	2W	3	4	5	6	7	8
1976	22	22	6	9	3	17	1	20	6	1	4
1977	24	10	1	9	0	16	1	23	4	2	9
1978	23	19	5	8	2	9	1	25	4	0	7
1979	15	19	6	3	6	10	0	29	3	0	14
1980	21	12	4	5	3	14	0	18	7	1	17
1981	13	11	4	3	3	13	0	37	9	0	6
1976-81											
% Distribution	21.9	17.3	-	-	-	14.7	0.6	28.8	6.1	0.7	10.6
Ave.	20	16	4	6	3	13	1	25	6	1	10
Std. Dev.	5	5	2	3	2	3	1	7	2	1	5
Std. Dev./Ave.	.25	.31	.50	.50	.67	.23	1.00	.28	.33	1.00	.50

Table A3

Spring Distribution of Synoptic Weather Classes Influencing Southern Ontario 1976-1981

	Weather Class										
Year	1	2	2N	2S	2W	3	4	5	6	7	8
1976	24	21	6	2	3	17	0	13	10	2	5
1977	24	18	12	1	0	13	1	13	8	3	13
1978	15	22	10	1	6	12	0	23	8	3	8
1979	13	15	6	0	3	15	8	23	5	3	10
1980	11	23	6	5	4	4	4	26	9	7	8
1981	12	19	8	1	5	17	5	15	15	0	6
1976-81											
% Distribution	18.0	21.5	-	-	-	14.2	3.3	20.6	10.0	3.3	9.1
Average	16	20	8	2	4	13	3	19	9	3	8
Std. Dev.	6	3	3	2	2	5	3	6	3	2	3
Std. Dev./Ave.	.38	.15	.38	1.00	.50	.38	1.00	.32	.33	.67	.38

Table A4

Summer Distribution of Synoptic Weather Classes Influencing Southern Ontario 1976-1981

	Weather Class										
Year	1	2	2N	2S	2W	3	4	5	6	7	8
1976	17	23	7	5	4	11	1	16	12	6	7
1977	16	14	6	2	5	21	2	7	11	7	14
1978	17	21	7	2	6	17	4	6	14	5	8
1979	14	21	6	2	6	10	4	18	10	2	13
1980	11	23	7	1	10	13	3	10	17	2	5
1981	14	14	6	1	6	16	5	17	11	4	12
1976-81											
% Distribution	16.3	21.2	-	-	-	16.1	3.5	13.6	13.7	4.8	10.8
Average	15	19	6	2	6	15	3	12	12	4	10
Std. Dev.	2	4	1	1	2	4	1	5	3	2	4
Std.Dev/Ave.	.13	.21	.17	.50	.33	.27	.33	.42	.25	.50	.40

Table A5

Fall Distribution of Synoptic Weather Classes Influencing Southern Ontario 1976-1981

	Weather Class										
Year	1	2	2N	2S	2W	3	4	5	6	7	8
1976	31	16	4	8	2	14	1	19	6	3	0
1977	25	17	3	9	1	22	2	11	3	4	8
1978	16	15	1	5	8	23	2	19	11	4	1
1979	9	13	3	4	4	20	4	26	9	3	6
1980	19	15	8	2	3	12	5	16	12	1	9
1981	20	20	9	4	4	13	0	21	7	0	9
1976-81											
% Distribution	22.1	17.5	-	-	-	19.3	2.6	20.6	8.8	2.8	6.1
Average	20	16	5	5	4	17	2	19	8	3	6
Std. Dev.	8	2	3	3	2	5	2	5	3	1	4
Std. Dev./Ave.	.40	.13	.60	.60	.50	.29	1.00	.26	.38	.33	.67

TD
885.5
.06
H35
1984